Claims

[c1] A method for reducing a spurious signal in a nuclear magnetic resonance (NMR) measurement, comprising:
inducing a static magnetic field in a volume to polarize spins of nuclei therein;
inducing an RF magnetic field in the volume in accordance with a pulse sequence;
acquiring a sequence of signals generated in the volume in response to the pulse sequence, each signal in the acquired sequence including a spurious signal component and a spin echo component;
combining at least a first signal and a second signal of the acquired sequence, thereby generating a corrected signal having a reduced spurious signal component.

[c2] The method as recited in claim 1, wherein the corrected signal is generated from a linear combination of at least the first signal and the second signal.

[c3] The method as recited in claim 2, wherein the linear combination is the average of at least the first signal and the second signal.

[c4] The method as recited in claim 1, wherein the second signal is adjacent the first signal in the acquired sequence.

[c5] The method as recited in claim 1, wherein the second signal is a next nearest neighbor of the first signal in the acquired sequence.

[c6] The method as recited in claim 1, wherein a time delay between the first signal and the second signal in the acquired sequence is less than 10 milliseconds.

[c7] The method as recited in claim 1, wherein a time delay between the first signal and the second signal in the acquired sequence is in the range of 0.5 to 5 milliseconds.

[c8] The method as recited in claim 1, comprising computing an NMR parameter of the volume using the corrected signal.

[c9]

The method as recited in claim 8, wherein the NMR parameter is a T_2

distribution.

[c10] The method as recited in claim 8, comprising deriving a geological characteristic of the volume based on the computed NMR property.

[c11] The method as recited in claim 10, wherein the geological characteristic is porosity.

[c12] The method as recited in claim 1, wherein the pulse sequence comprises a plurality of inversion pulses, and wherein at least one of the inversion pulses is phase alternated relative to the others.

[c13] The method as recited in claim 1, wherein the pulses of the pulse sequence are arranged to compensate for spin dynamics errors.

[c14] The method as recited in claim 1, wherein the pulse sequence comprises a plurality of inversion pulses arranged in a repeating phase pattern, and wherein the repeating phase pattern is six inversion pulses arranged to induce a phase pattern of six spin echo signals in accordance with the following:

$$+\mathbf{X}_1(-y_1)-\mathbf{X}_2(+y_2)-\mathbf{X}_3(-y_3)-\mathbf{X}_4(+y_4)+\mathbf{X}_5(-y_5)+\mathbf{X}_6(+y_6)$$

wherein the bold uppercase terms represent direction of the inversion pulses, and the italicized lowercase terms represent direction of the induced spin echo signals in a rotating frame of reference.

[c15] The method as recited in claim 14, wherein the linear combination is selected from the group consisting of:

(a) $lc_1 = \frac{1}{2}(e_i + e_j)\forall\ i = 1, 4, 7, \ldots,\ j = 3, 6, 9, \ldots;$

(b) $lc_2 = \frac{1}{2}(e_i + e_j)\forall\ i = 2, 5, 8, \ldots,\ j = 3, 6, 9, \ldots;$

(c) $lc_3 = \frac{1}{2}(e_i + e_j)\forall\ i = 3, 6, 9, \ldots,\ j = 4, 7, 10, \ldots;$

(d) $lc_4 = \frac{1}{2}(e_i + e_j)\forall\ i = 3, 6, 9, \ldots,\ j = 5, 8, 11, \ldots;$

wherein *lc* represents the linear combination, and *e* represents the induced spin echo signal.

[c16]

The method as recited in claim 1, wherein the pulse sequence comprises a plurality of inversion pulses arranged in a repeating phase pattern, and wherein the repeating phase pattern is three inversion pulses arranged to induce a

phase pattern of three spin echo signals in accordance with the following:

$$+\mathbf{Y}_1(+y_1)-\mathbf{Y}_2(+y_2)-\mathbf{Y}_3(+y_3)$$

wherein the bold uppercase terms represent direction of the inversion pulses, and the italicized lowercase terms represent direction of the induced spin echo signals in a rotating frame of reference.

[c17] The method as recited in claim 1, wherein the pulse sequence comprises a plurality of inversion pulses arranged in a repeating phase pattern, and wherein the repeating phase pattern is three inversion pulses arranged to induce a phase pattern of three spin echo signals in accordance with the following:

$$+\mathbf{Y}_1(+y_1)+\mathbf{Y}_2(+y_2)-\mathbf{Y}_3(+y_3)$$

wherein the bold uppercase terms represent direction of the inversion pulses, and the italicized lowercase terms represent direction of the induced spin echo signals in a rotating frame of reference.

[c18] The method as recited in claim 1, comprising computing a first reconstructed signal and a second reconstructed signal from the corrected signal, the first and second reconstructed signals representative of the respective spin echo components of the first and second signals of the acquired sequence.

[c19]

A method of reducing a ringing signal generated while measuring a nuclear magnetic resonance (NMR) property of an earth formation adjacent a borehole, comprising:

inserting a logging tool into the borehole;

applying a static magnetic field to polarize spins of nuclei within a volume of the earth formation;

applying an RF magnetic field to the volume in accordance with a pulse sequence comprising a plurality of inversion pulses arranged in a repeating phase pattern;

acquiring, after each of the plurality of pulses in the pulse sequence, a spin echo signal induced in the volume, thereby forming a measurement set comprising a plurality of spin echo signals, each spin echo signal including a spin echo component and a ringing component; and

combining spin echo signals within the measurement set to reduce the ringing

components, thereby generating a corrected measurement set.

[c20] The method as recited in claim 19, wherein the combining comprises forming a linear combination of spin echo signals within the measurement set.

[c21] The method as recited in claim 19, comprising determining, from the corrected measurement set, an NMR parameter of the earth formation.

[c22] The method as recited in claim 21, comprising deriving from the NMR parameter a property of the earth formation.

[c23] The method as recited in claim 19, wherein the acquiring is performed while drilling the borehole.

[c24] The method as recited in claim 19, wherein at least one of the inversion pulses in the repeating phase pattern is phase alternated relative to the others.

[c25] The method as recited in claim 19, wherein the inversion pulses in the repeating phase pattern are arranged to compensate for spin dynamics errors.

[c26] The method as recited in claim 19, wherein the repeating phase pattern of inversion pulses is six inversion pulses arranged to induce a pattern of six spin echo signals in accordance with the following:

$$+\mathbf{X}_1(-y_1)-\mathbf{X}_2(+y_2)-\mathbf{X}_3(-y_3)-\mathbf{X}_4(+y_4)+\mathbf{X}_5(-y_5)+\mathbf{X}_6(+y_6)$$

wherein the bold uppercase terms represent direction of the inversion pulses, and the italicized lowercase terms represent direction of the induced spin echo signals in a rotating frame of reference.

[c27] The method as recited in claim 26, wherein the combining comprises forming a linear combination of spin echo signals within the measurement set, and the linear combination is selected from the group consisting of:

(a) $lc_1 = \frac{1}{2}(e_i + e_j)\forall \quad i = 1, 4, 7, \ldots, j = 3, 6, 9, \ldots;$

(b) $lc_2 = \frac{1}{2}(e_i + e_j)\forall \quad i = 2, 5, 8, \ldots, j = 3, 6, 9, \ldots;$

(c) $lc_3 = \frac{1}{2}(e_i + e_j)\forall \quad i = 3, 6, 9, \ldots, j = 4, 7, 10, \ldots;$

(d) $lc_4 = \frac{1}{2}(e_i + e_j)\forall \quad i = 3, 6, 9, \ldots, j = 5, 8, 11, \ldots;$

wherein *lc* represents the linear combination, and *e* represents the induced spin echo signal.

[c28] The method as recited in claim 19, wherein the repeating phase pattern of inversion pulses is three inversion pulses arranged to induce a pattern of three spin echo signals in accordance with the following:

$$+\mathbf{Y}_1(+y_1)-\mathbf{Y}_2(+y_2)-\mathbf{Y}_3(+y_3)$$

wherein the bold uppercase terms represent direction of the inversion pulses, and wherein the italicized lowercase terms represent direction of the induced spin echo signals in a rotating frame of reference.

[c29] The method as recited in claim 19, wherein the repeating phase pattern of inversion pulses is three inversion pulses arranged to induce a pattern of three spin echo signals in accordance with the following:

$$+\mathbf{Y}_1(+y_1)+\mathbf{Y}_2(+y_2)-\mathbf{Y}_3(+y_3)$$

wherein the bold uppercase terms represent direction of the inversion pulses, and the italicized lowercase terms represent direction of the induced spin echo signals in a rotating frame of reference.

[c30] The method as recited in claim 19, comprising computing a set of first reconstructed signals from the corrected measurement set, the set of reconstructed signals representative of the respective spin echo components of the acquired spin echo signals.

[c31] A method for determining an earth formation property from nuclear magnetic resonance (NMR) measurements, comprising:
acquiring a first measurement set of spin echo signals induced in the earth formation by a first RF pulse sequence, the spin echo signals including a spin echo component and a noise component;
linearly combining spin echo signals within the first measurement set to reduce the noise component, thereby generating a first corrected measurement set;
determining an NMR parameter based on the first corrected measurement set; and
deriving the earth formation property from the NMR parameter.

[c32] The method as recited in claim 31, wherein the linearly combining is restricted to only combinations of spin echo signals that reduce the noise component.

[c33] The method as recited in claim 31, wherein the NMR parameter is a T_2 distribution.

[c34] The method as recited in claim 31, wherein the acquiring is performed while drilling a borehole traversing the earth formation.

[c35] The method as recited in claim 31, comprising:
acquiring a second measurement set of spin echo signals induced in the earth formation by a second RF pulse sequence, the second RF pulse sequence being phase alternated relative to the first RF pulse sequence, the spin echo signals of the second measurement set including a spin echo component and a noise component;
linearly combining spin echo signals within the second measurement set to reduce the noise component, thereby generating a second corrected measurement set;
combining the first corrected measurement set with the second corrected measurement set; and
determining the NMR parameter based on the first and second corrected measurement sets.

[c36] The method as recited in claim 31, wherein the first RF pulse sequence comprises a plurality of inversion pulses arranged in a repeating phase pattern, and wherein the repeating phase pattern is six inversion pulses arranged to induce a pattern of six spin echo signals in accordance with the following:

$$+\mathbf{X}_1(-y_1)-\mathbf{X}_2(+y_2)-\mathbf{X}_3(-y_3)-\mathbf{X}_4(+y_4)+\mathbf{X}_5(-y_5)+\mathbf{X}_6(+y_6)$$

wherein the bold uppercase terms represent direction of the inversion pulses, and the italicized lowercase terms represent direction of the induced spin echo signals in a rotating frame of reference.

[c37] The method as recited in claim 36, wherein linearly combining comprises forming at least one linear combination from the group consisting of:

(a) $lc_1 = \frac{1}{2}(e_i + e_j) \forall \; i = 1, 4, 7, \ldots, j = 3, 6, 9, \ldots;$

(b) $lc_2 = \frac{1}{2}(e_i + e_j) \forall \; i = 2, 5, 8, \ldots, j = 3, 6, 9, \ldots;$

(c) $lc_3 = \frac{1}{2}(e_i + e_j) \forall \; i = 3, 6, 9, \ldots, j = 4, 7, 10, \ldots;$

(d) $lc_4 = \frac{1}{2}(e_i + e_j) \forall \; i = 3, 6, 9, \ldots, j = 5, 8, 11, \ldots;$

wherein *lc* represents the linear combination, and *e* represents the induced spin echo signal.

[c38] The method as recited in claim 31, wherein the first RF pulse sequence comprises a plurality of inversion pulses arranged in a repeating phase pattern, and wherein the repeating phase pattern is three inversion pulses arranged to induce a pattern of three spin echo signals in accordance with the following:

$$+\mathbf{Y}_1(+y_1)-\mathbf{Y}_2(+y_2)-\mathbf{Y}_3(+y_3)$$

wherein the bold uppercase terms represent direction of the inversion pulses, and the italicized lowercase terms represent direction of the induced spin echo signals in a rotating frame of reference.

[c39] The method as recited in claim 31, wherein the first RF pulse sequence comprises a plurality of inversion pulses arranged in a repeating phase pattern, and wherein the repeating phase pattern is three inversion pulses arranged to induce a pattern of three spin echo signals in accordance with the following:

$$+\mathbf{Y}_1(+y_1)+\mathbf{Y}_2(+y_2)-\mathbf{Y}_3(+y_3)$$

wherein the bold uppercase terms represent direction of the inversion pulses, and the italicized lowercase terms represent direction of the induced spin echo signals in a rotating frame of reference.

[c40] The method as recited in claim 31, comprising computing a first reconstructed signal and a second reconstructed signal from the corrected signal, the first and second reconstructed signals representative of the respective spin echo components of the first and second signals of the acquired sequence.